

Citation for published version:

Xing, D, Patel, J, Sun, Q, Zhu, J, Zhang, G, Liang, F, Yuan, W & Zhang, M 2017, 'AC loss comparison between multifilament and nonstriated YBCO coils designed for HTS propulsion motors', *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, 5203005. <https://doi.org/10.1109/TASC.2017.2669156>

DOI:

[10.1109/TASC.2017.2669156](https://doi.org/10.1109/TASC.2017.2669156)

Publication date:

2017

Document Version

Peer reviewed version

[Link to publication](#)

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AC Loss Comparison between Multi-filament and Non-striated YBCO Coils Designed for HTS Propulsion Motors

Dong Xing, Jay Patel, Qixing Sun, Jiahui Zhu, Guomin Zhang, Fei Liang, Weijia Yuan and Min Zhang

In this paper, the properties of current capacity and AC transport loss of striated HTS coil is compared with ordinary HTS coil by using both experimental and simulation methods. The measurements were carried out by transporting a sinusoidal varying current at 77K, with an amplitude range of 10-50A in frequency from 70Hz up to 300Hz. Measurement facilities and methods are explained in more detail in the paper. The critical current of the 4mm width multi-filament coil made with 4 filaments at a spacing 0.03mm was found to be lower than that of the non-striated coil. The frequency dependent characteristics agreed well in both experimental and simulated results. Reducing AC loss of HTS is one enabling factor for widespread adoption of the technology and therefore understanding its characteristics is important and discussed in this paper. Future plans based on this preliminary work is the testing of multi-filament tapes in an axial flux motor field environment.

Index Terms— AC loss, Superconducting coils, Multi-filament superconductors, Loss measurement.

I. INTRODUCTION

YBCO coated conductors are regarded as one of the most promising coated conductors due to their high current density and ability to maintain high critical current within strong magnetic fields [1]. Of the handful of barriers preventing widespread adoption of HTS technology is the problem of AC losses. Indeed, many applications of superconductors that allow them to integrate into live systems require alternating current to be carried i.e. motors, generators or transformers. AC losses and remnant fields can be reduced by using multi-filament tapes, as found by Brandt, the magnetization loss follows a square law with the width of the superconductor [2]. Multi-filament tape is striated using a variety of techniques, the most popular methods are laser scribing or chemical etching. The improvement of manufacturing techniques have allowed the use of narrower filaments and results have proved that the thinner the individual filaments, the lower the undesirable AC losses. Additionally, striated HTS can also

reduce current inhomogeneity caused by screening currents, which are crucial to applications such as NMR and MRI.

A great number of research groups as well as manufacturers have been focusing on investigating the magnetization AC loss and transverse resistivity of striated tapes [3-8]. Lots of researchers has confirmed that striation is an effective way to reduce the hysteresis AC losses. Meanwhile, the coupling loss becomes more important with an increase in the number of filaments. The superconductor can experience full filament uncoupling to full coupling within a specific frequency range [4]. Majoros et al. gave more explanations on the screening current coupled in both striated and monolayer samples [9]. Although lots of results have been gained for straight tape ‘in-field’ scenarios, the transport AC loss of YBCO CC coils is an aspect which cannot be ignored with applied current. Majoros et al. compared the transport AC loss between striated (multi-filament) and non-striated YBCO CC tape and addressed that the frequency dependence for transport loss is rather weak and mainly determined by the losses in the substrate and Ni layer up to currents of about 50% of the critical current [10]. Finite element methods are an effective way to analyze the critical state and characteristics of the coil. F. Grilli et al. [11], Z. Hong et al. [12], E. Pardo et al. [13], Souc et al. [14] and M. Zhang et al. [15] have promoted the numerical scheme for AC loss calculation to more efficient levels. M. Zhang et al. has used an experimentally verified H-Formulation to study air cored and distributed windings in motors [16]. However, the transport AC loss of multi-filament YBCO coils have not been discussed clearly in both experiment and simulation parts. Therefore, we will investigate the properties of transport AC loss of multi-filament and non-striated coils by using both experimental and finite element method of an axial symmetrical model combining the methods presented by Z. Hong et al. in [12] and M Zhang et al. in [15].

In this paper, we present the critical current measurement as well as the AC transport loss measurement of two coils wound by multi-filament YBCO CC and normal non-striated YBCO CC manufactured by Superpower. The width and thickness of both of the tapes are same. Critical currents and the transport AC losses are measured using the four-point and compensation method. Experimental results are also compared with simulated results. The coils considered are intended to be used in a prototype axial flux motor; a model for considering the AC loss by coupling a machine model with a HTS model was proposed by M. Zhang et al. [17] and will be used to verify the machine results in high-frequency propulsion situation.

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Fig. 1. Multi-filament sample coil (left) and non-striated sample coil (right) wound by YBCO coated conductors.

II. EXPERIMENT

A. Sample Preparation

Two sample coils wound using YBCO coated conductors were manufactured and are shown in figure 1. The tapes used are supplied by Superpower. The width and the length of the two striated and non-striated tapes are identical with a width and length of 4mm and 2.76m respectively. The tapes consist of 50 μm hastelloy substrate and 2 μm silver protective layer. The Kapton[®] film thickness is 0.03mm, total tape thickness with adhesives is 0.10mm with 0.04mm adhesive on each side. The multi-filament tape has 4 filaments with a 0.03mm gap per filament. The measurements were carried out using two sample holders which have outer and inner diameters of 8.9cm and 7cm. Both of the coils are wound with 9.5 turns. More details are listed in Table 1.

TABLE I

	Striated coil	Non-striated coil
Wire Type	SCS4050-AP	SCS4050-AP-i
Tape width	4mm	4mm
Total tape length (m)	2.76	2.76
Number of filaments	4	-
Filament width(mm)	0.978	-
Tape I_c (A)	90	103
Number of Turns	9.5	9.5
Coil radius (mm)	44.5mm	44.5mm
Frequency range (Hz)	70-300	70-300
Coil I_c (A)	66	71

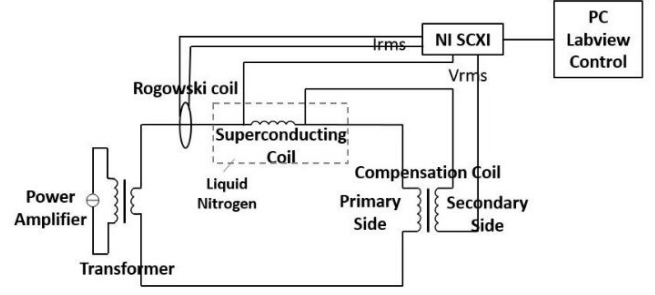


Fig. 2. Measurement scheme of the transport AC loss measurement

B. Critical Current Measurements

The critical current of the coils is measured by the four-point method using a $1 \mu\text{V}/\text{cm}$ criterion in self-field conditions in the liquid nitrogen at 77 K operating temperature. The ramp rate of the applied current can be controlled with LabVIEW and NI data acquisition module at 1 A/s. A LabVIEW interface panel is used to control the DC power supply. The maximum voltage through the HTS sample is set as 10 times the critical voltage.

C. AC Transport Loss Measurements

The AC loss testing system we used in this measurement is based on the experiment system established and explained by Z. Jiahui et al.[18]. The AC loss measurement system panel is shown in Fig. 2. A sinusoidal signal waveform is supplied by a 20kW power amplifier which is connected to a transformer. The Rogowski coil is used to measure the applied current from the secondary side of the transformer. To get a pure resistive voltage, a cancellation coil has been connected in series with the measured superconducting coil and the secondary side of the transformer to cancel the inductive voltage produced due to a time varying applied transport current. The self-field AC transport loss of the superconducting coil per unit length per cycle can be calculated by equation 1:

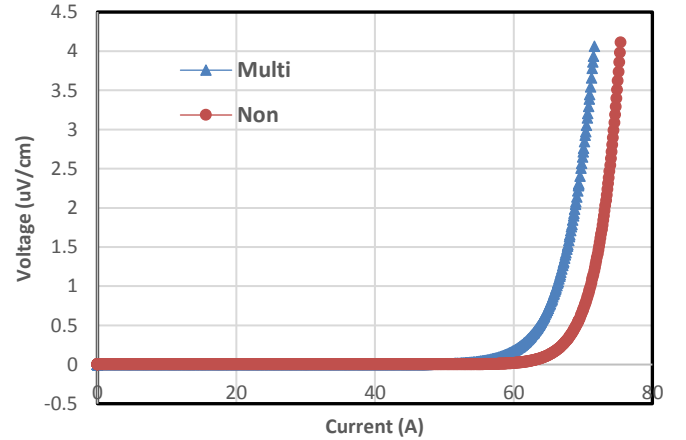


Fig. 3. Critical current of multi-filament coil (left line) and non-striated coil (right line) after processed in MATLAB.

$$Q = \frac{V_{rms} I_{rms}}{fL} \quad (1)$$

where V_{rms} and I_{rms} are RMS values of pure resistive loss voltage and the AC transport current of the superconductor is in phase with V_{rms} between the two voltage taps. ' f ' is the frequency. ' L ' is the length between two voltage taps. The range of I_{rms} is varied from 10 to 50A owing to the limits of the power amplifier supply. The in-phase voltage and current can be observed from the Labview software. When the resistive voltage is cancelled well by the cancellation coil, the sinusoidal voltage and current line will coincide. There are five frequencies chosen: 70, 120, 170, 220 and 300Hz.

III. RESULTS

A. Critical Current

Figure 3 indicates the DC current and voltage characteristics for striated and non-striated coils, the coil with no strips has the higher critical current which is around 71A. Due to the removal of superconducting material, the critical current of the multi-filament coil is 66A which is about a 7% degradation of the non-striated coil. In regards to the filament

width, the cut groove is quite thin (0.03mm), whereas the critical current still decreases a lot for a 9.5-turn coil. The n values are calculated by MATLAB, which are 18 and 24 for the multi-filament and non-striated coils respectively.

B. AC Losses

The experimental measurement results of transport AC loss of multi-filament and non-striated coils are shown in figure 4. Both of them are applied with the same current and in the same frequency range 70Hz to 300Hz. The rms current range for most of the tests is from 10A to 50A. The peak current range for most of the tests is from 14A to 71A. The rms current cannot reach 50A for higher frequency, due to the upper limits of the internal oscillator output of the power amplifier in our lab. Compared with the multi-filament coil, a larger difference can be witnessed from figure 4(b) where the AC losses of the non-striated coil at 170Hz is higher than the AC losses at 70Hz with lower transporting current. It indicates that at lower currents, the AC losses of the multi-filament coil are more independent of frequency than the non-striated coil.

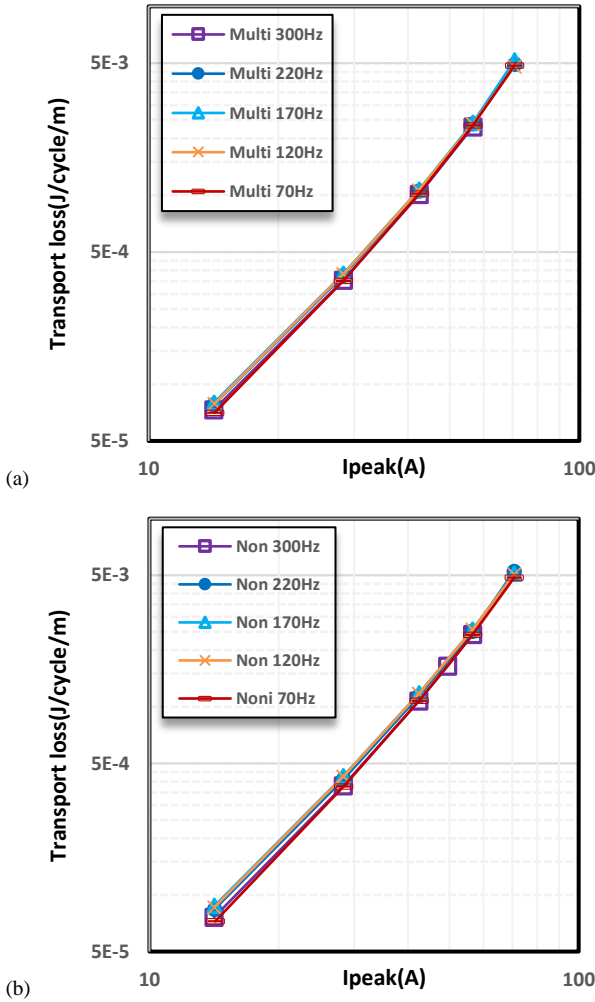


Fig. 4. Transport AC loss of (a) Multi-filament and (b) non-striated coils with various applied currents measured in the frequency range 70Hz to 300Hz and peak current range from 14A to 70A.

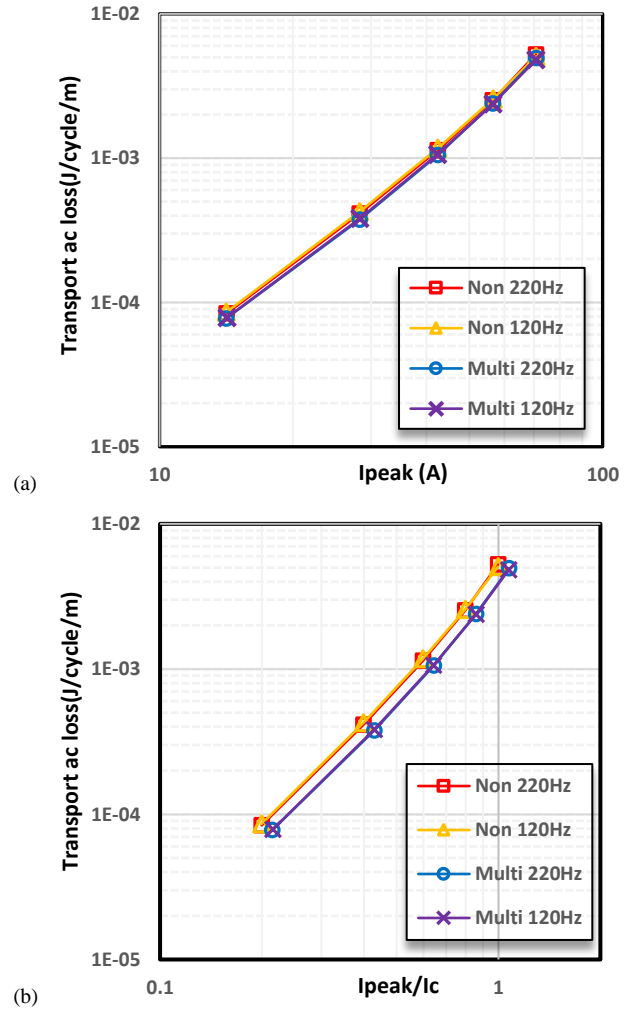


Fig. 5. Comparison of the transport AC loss with (a) applied current and (b) normalized current of multifilamentary and non-striated coils derived from experiment in the frequency range 70Hz to 300Hz.

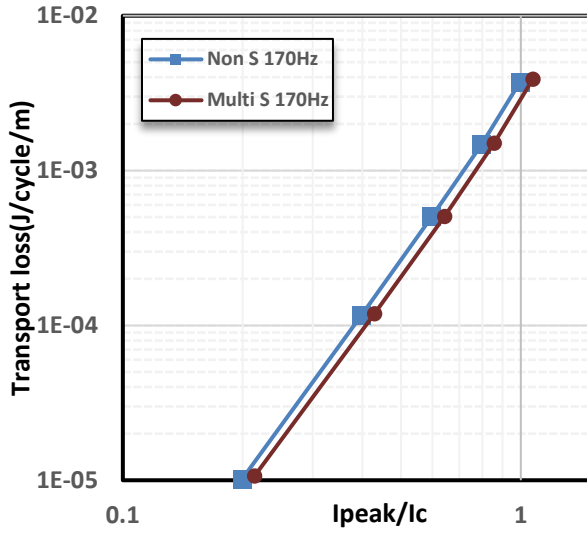


Fig. 6. Comparison of the transport AC loss with normalized current of multi-filament and non-striated coils derived from simulation in 170Hz.

For AC losses comparison with applied current and normalized current, only two groups of results are used (120Hz and 220Hz). There is not a big difference between multi-filament and non-striated coils in the experimental results shown in fig.5 (a) with the same applied current. However, one can still see the transport AC losses of the multi-filament coil are slightly lower than those of the non-striated one. The comparison results of transport AC loss plotted against the normalized current (divided by I_c) is shown in figure 5 (b). It is more obvious to see the difference between the two measured coils. The reduction for the multi-filament coil is about 20% for the same normalized current, which is a very good feature.

According to the results in [3-8], larger width of grooves or more number of filaments for the same width of the tape leads to lower AC losses. In our experiment, there are only 4 filaments in one tape. The groove of the multi-filament tape used in our experiment is 0.03mm wide. The coupling loss originating from the metallic connections among the filaments increases the total AC losses in the multi-filament coils which has been proved in [1].

C. Simulation Results

Fig. 6 presents the simulated results of the multi-filament coil derived from COMSOL using finite element methods with H Formulation [12, 15]. We used equation 2 to calculate transport AC loss Q (J/cycle) in the simulation work [19].

$$Q = \int_t [\sum_1^N 2\pi r \int_s E_\phi \cdot J_\phi dS] dt \quad (2)$$

where 'S' is the cross section of a single turn, and 'N' denotes the total turns. E_ϕ and J_ϕ are electric field and current density in the direction of ϕ . 'r' represents the radius of the N th turn. The J_c we used in this simulation is constant. In figure 6, we compare the simulated results in the frequency of 170Hz. For both coils we used 10 turns. To compare it with the measured results we divide the transport AC loss Q by the total length of the coil. As can be seen from the figure, the multi-filament coil has the lower transport AC losses as we applied the same

normalized current. The AC loss reduction reaches 25%. Compared with the measurement results, the simulation results show a better transport AC loss reduction. For each coil, the simulated results are lower than the measurement results. One main reason is that the model ignores the coupling losing of the coated conductor in the simulation.

IV. CONCLUSION

In this work experimental results of AC transport loss for both multi-filament and non-striated coil wound by YBCO coated conductors were analyzed. The critical current of multi-filament coil is 66A which is 5A lower than the non-striated coil but with only 0.03mm cut groove. Striation process indeed decreases the AC transport current but not as much as we expected. The normalization has good effects on the transport AC loss reduction in our measurement. A 20% drop can be reached for a 9.5-turn multi-filament coil with the same normalized current from the measured results. The same situation can also be found in the simulation results with a 25% decrease in the transport AC loss.

ACKNOWLEDGMENT

This study is supported by Royal Academy of Engineering Research Fellowship and EPSRC council grant (EP/P002277/1) for Dr Min Zhang. Jay Patel would like to acknowledge the ASC financial support. We also thank Superpower for kindly providing the multi-filament tape.

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